REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
23 August 2017

2. REPORT TYPE
Briefing Charts

3. DATES COVERED *(From - To)*
01 August 2017 - 31 August 2017

4. TITLE AND SUBTITLE
Study of Combustion Characteristics of Hydrocarbon Nanofuel Droplets

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Alireza Badakhshan, John Bennewitz and Douglas Talley

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q0YA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQRC
10 E. Saturn Blvd.
Edwards AFB, CA 93524-7680

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2017-203

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited. PA Clearance Number: 17513 Clearance Date: 18 August 2017.

13. SUPPLEMENTARY NOTES
For presentation at ONR/ARO/AFOSR Meeting; Rosslin, VA, USA; 21-25 August 2017.
Prepared in collaboration with ERC and UCLA. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT
Viewgraph/Briefing Charts

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Douglas Talley
					19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	SAR	27	N/A

Study of Combustion Characteristics of Hydrocarbon Nanofuel Droplets

A. Badakhshan*, J. Bennewitz**, and D. Talley†

*ERC Inc., Edwards AFB, CA
**University of California Los Angeles
†Air Force Research Laboratory, Aerospace Systems Directorate,
Combustion Devices Group, Edwards AFB, CA

ONR/ARO/AFOSR Meeting, 23 Aug., 2017

Objectives and Overview

Goal of the Project:

- Control of combustion dynamics of hydrocarbon fuels through solid nano-energetic additives.
- This is a multi-task project, which includes the following steps:

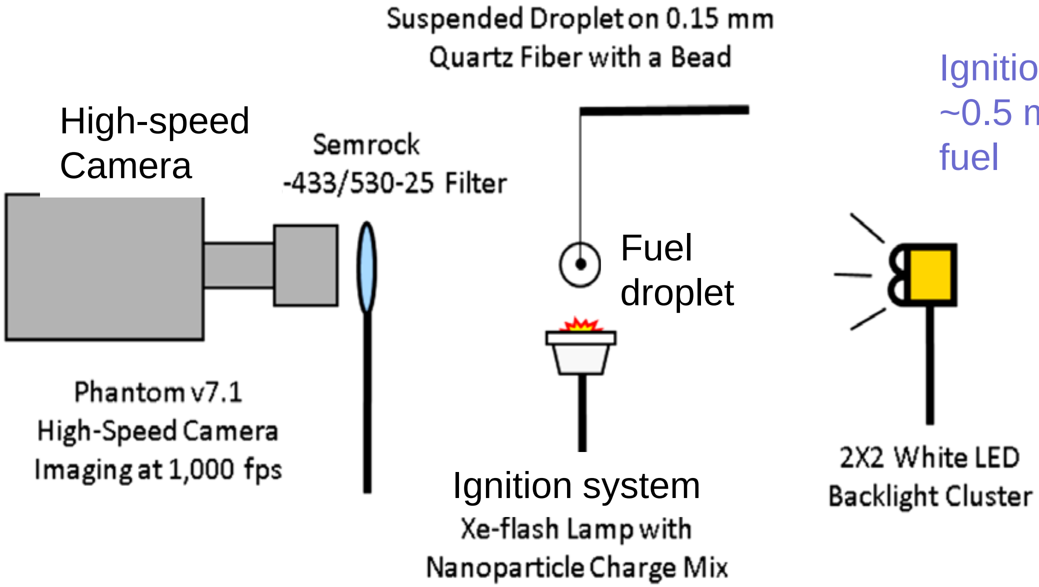
- Combustion Characteristics of Suspended Droplets of Hydrocarbon Fuels:

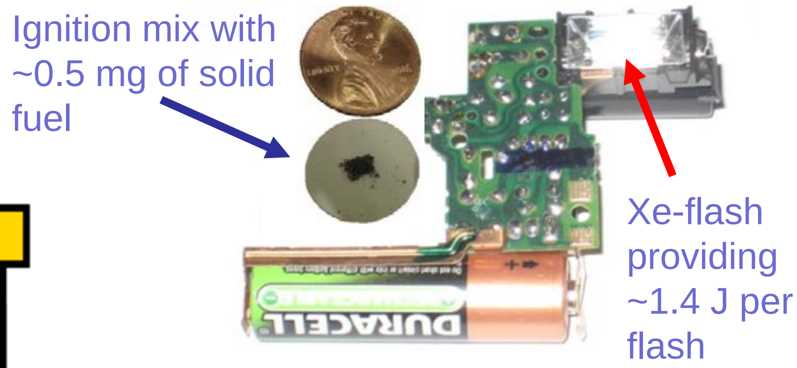
- Create baseline results for hydrocarbon fuels at ambient conditions (completed.)
- Identify nano-energetic fuel additives, which could potentially significantly influence combustion characteristics (current work.)

- Study of Nanofuel Spray Burning at High Pressures:

- Study combustion characteristics and ignition transient for nanofuel sprays under subcritical (<450 psi) conditions in a sacrificial pressure vessel.
- Investigate combustion dynamics of nanofuel sprays under acoustic forcing at supercritical conditions (>600 psi) in our combustion inability facility.

Ignition of a Suspended Droplet by Photoignition and Plasma Arc Ignitor

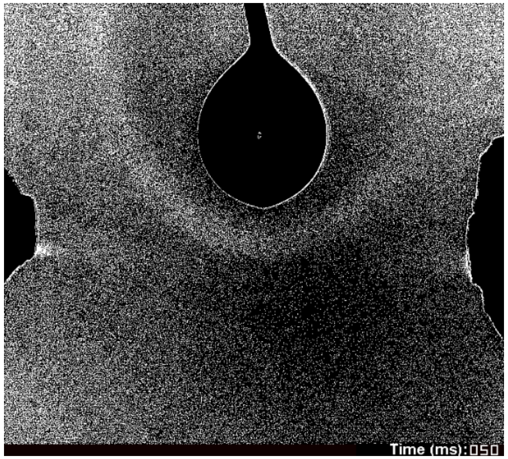




A basic photoignition (PI) system

Activation of the Xe-flash leads to photoignition of Al nanoparticles

PI plume in action



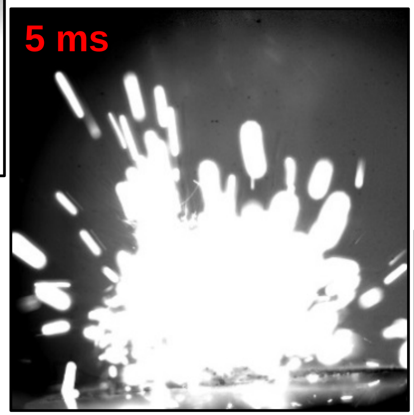
Plasma Arc Ignitor in action

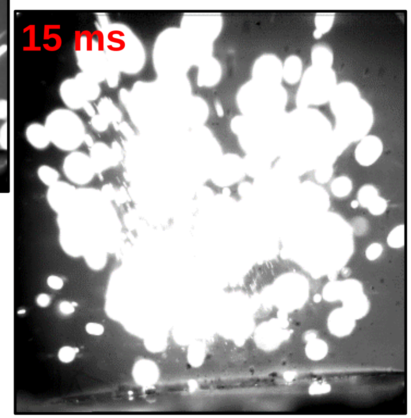
Justification for Using Fast-acting Ignition Methods

- Photoignition (PI) and plasma arc ignitor (PAI) proved to be well-suited for the study of burning characteristics of fuel droplets.
- Advantages of PI and PAI compared to conventional ignition methods:
  - Short ignition duration <120 ms vs >500 ms,
  - High ignition temperature (>2000 K) vs <1300 K, and
  - Much lower heat transfer due to low energy consumption
- The short ignition duration facilitates the observation of ignition delay, the onset of quasi steady burning and the “two-stage ignition” in droplets.
- PI is applicable up to 1000 psi and PAI is applicable <250 psi.
- PI ejects burning nanoparticles (typically nAl) that may:
  - Potentially contaminate the fuel droplet
  - May initially interfere with imaging due bright particles
- We first used PI for neat fuels, but later we switched to plasma arc ignitor due to potential contamination of the droplet
- PAI is least intrusive with no interference with flame imaging.

Photoignition of Al NPs as it Leads to the Combustion of a Fuel Droplet

Burning of Al NPs after Xe-Flash activation



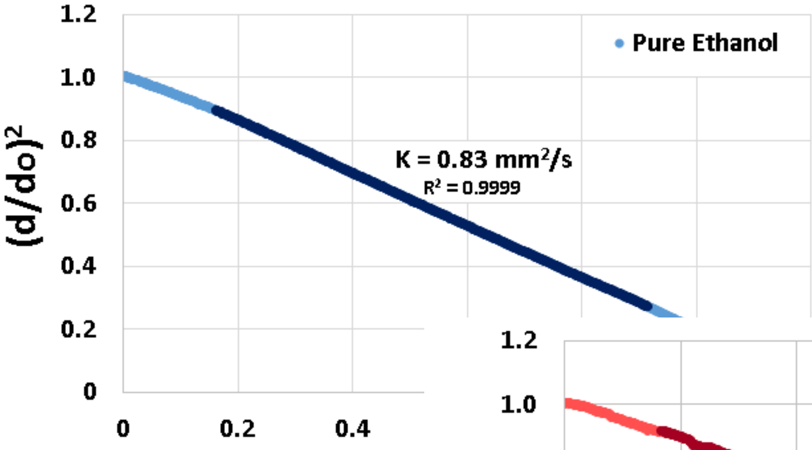


Al NPs burn very hot (>2000 K), the burning may last ~ 100 ms

Burning of a suspended RP-2 droplet with D = 1.4 ± 0.1 mm

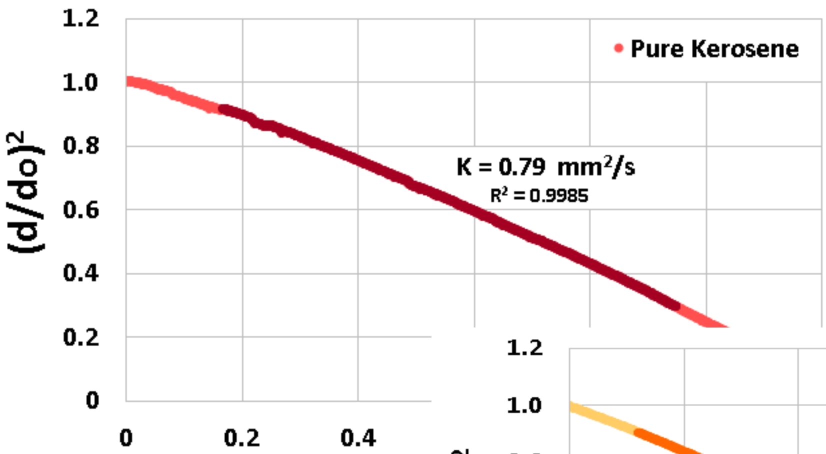
We used two fast-acting ignition methods, (~100 ms), either photoignition or plasma arc ignition. We also performed a few Ni-Cr heating coil ignition (~500 ms), to confirm that the ignition method had no adverse effects on the burn duration

Evaluation of Burning Rate Constant, *K* (from Diameter Tracking Data for Different Fuels)

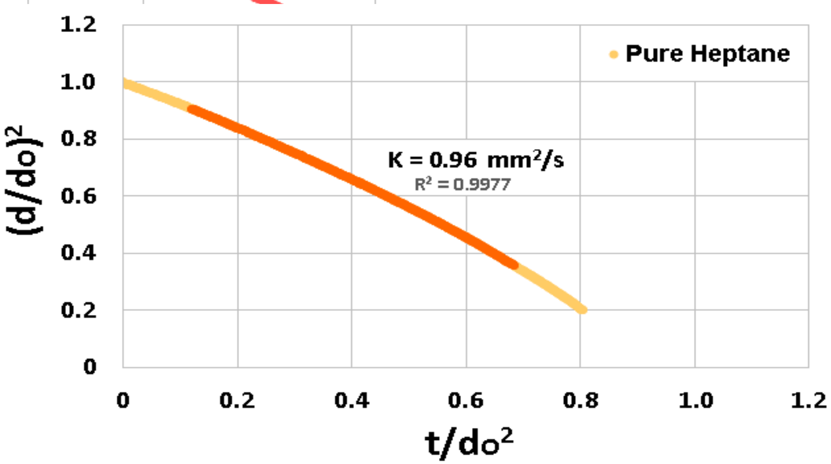


$K_{mid.,70}$ (70% of data around mid point), transient effects at the beginning and the end are excluded

Quasi steady burning of ethanol is most linear, so *K* is least sensitive to the evaluation method



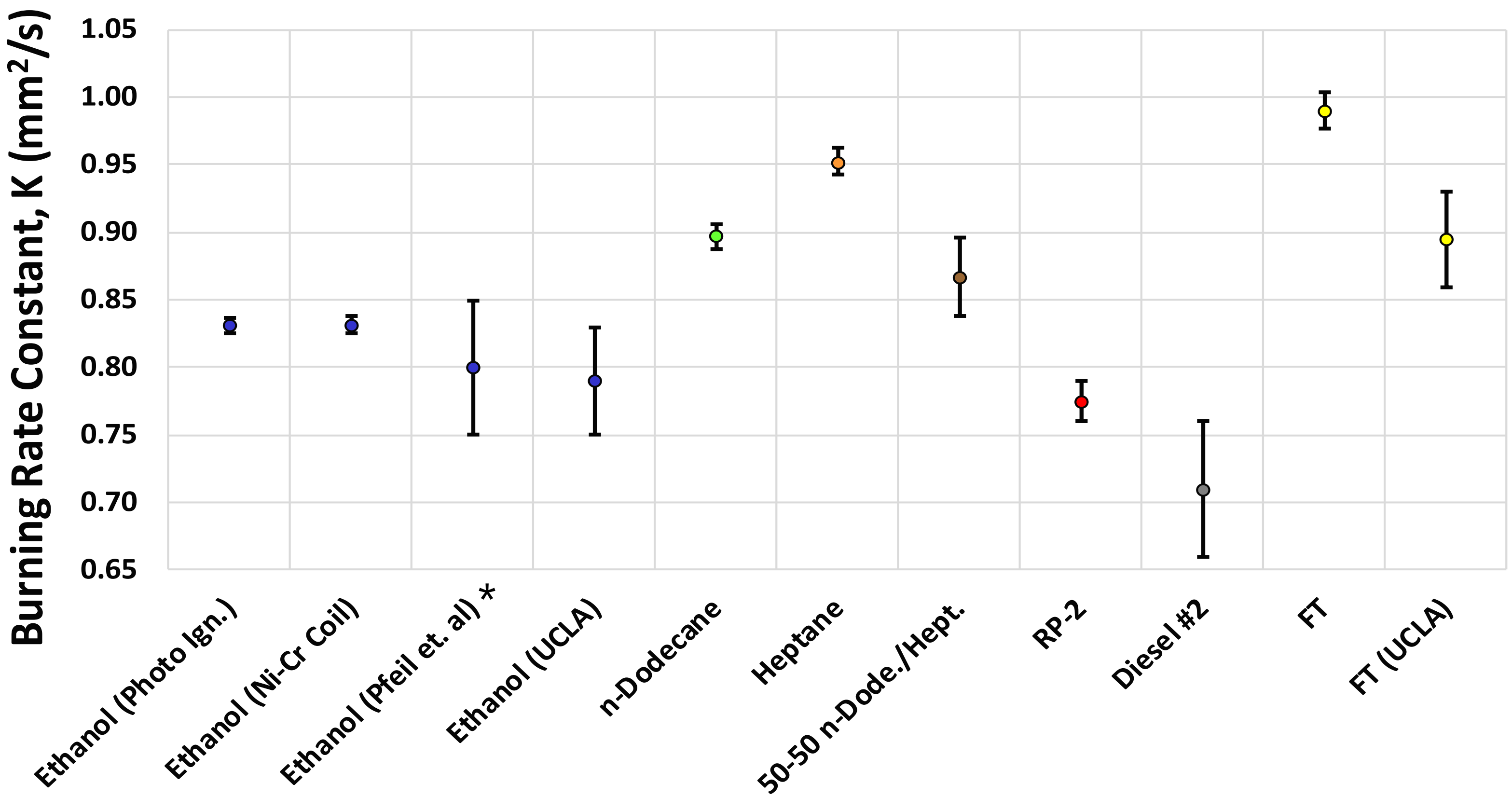
RP-2 burning curve is in between the other two



Quasi steady burning of Heptane is most nonlinear, so *K* is quite sensitive to the evaluation method and any deviations from $K_{mid.,70}$ results in the most changes in *K* that in some fuels can be up to 25%.

Burning Rate Constants (*K*) for Different Neat Fuel Droplets

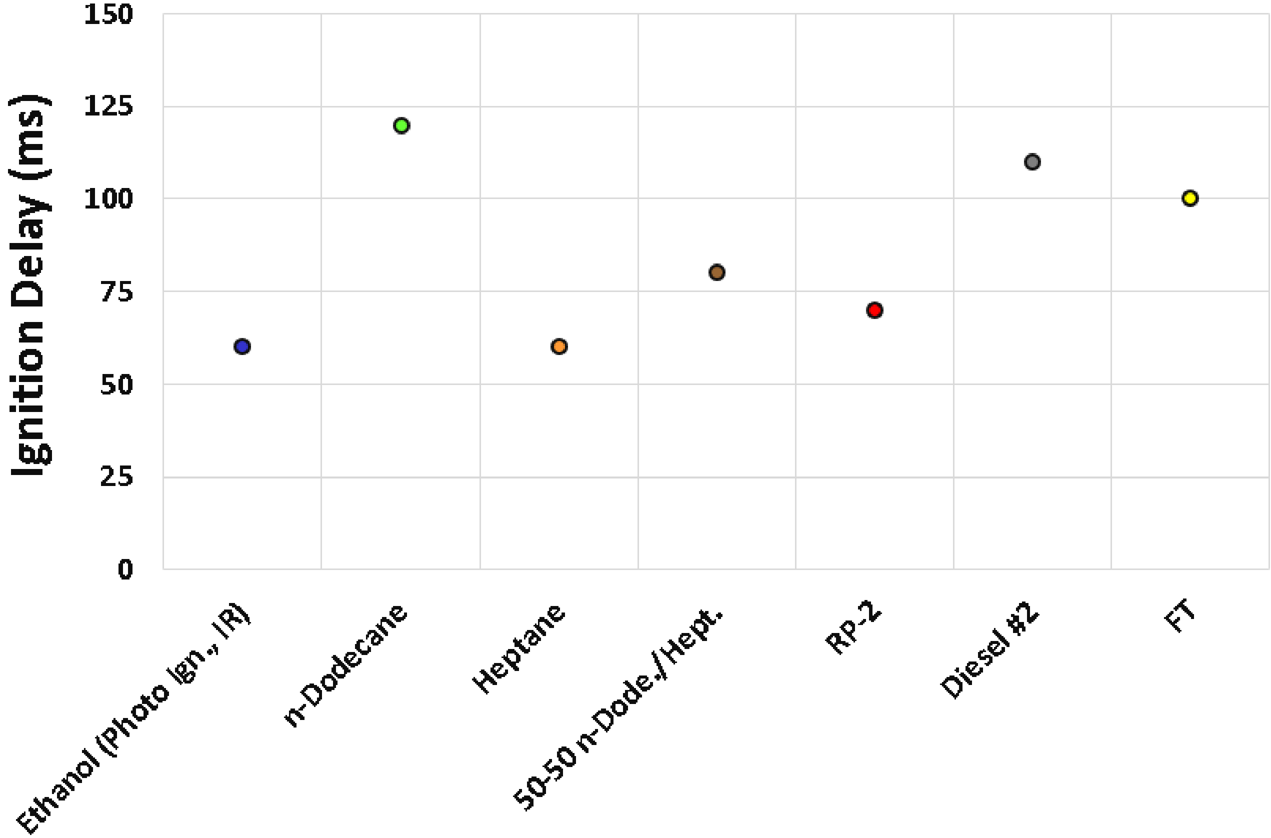
K values are consistent with other labs



* Pfeil et., al, *Combustion and Flame* (2013)

- *K* values are based on multiple series of 15 tests for each fuel (-Diesel #2.), D= 1.4 ± 0.1 mm.
- For consistency, we only report $K{=}K_{mid.,70}$, though it may not be the best value in specific cases
- Statistical uncertainties associated with the evaluation method for *K* can be as large as ± 10%

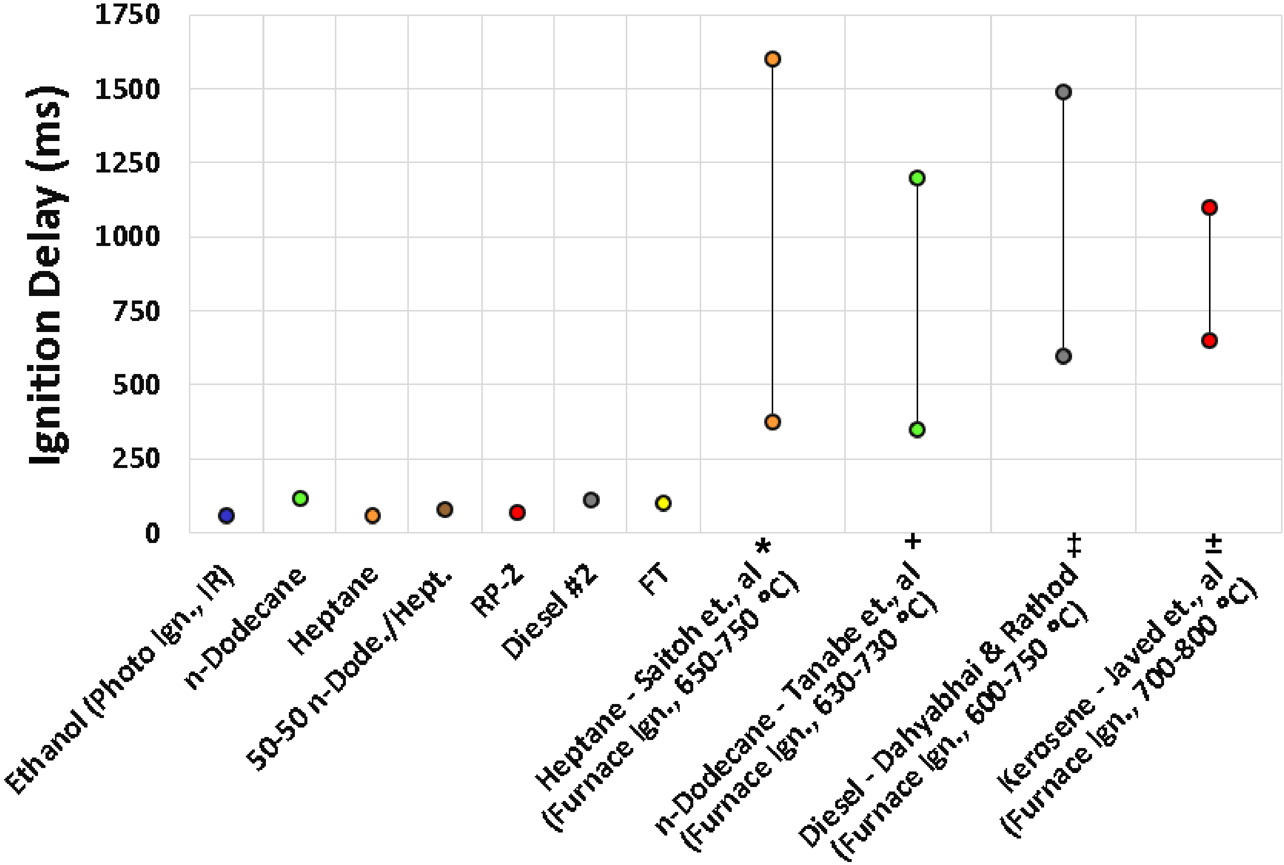
Ignition Delay for Neat Hydrocarbon Fuel Droplets



- Performed multiple series of 4-6 tests for each fuel to “estimate” $\tau_{ign.}$ through visual inspection of high-speed images (no error bars.)
- Ignition delay was defined as the time from the Xe-flash to the initial flame appearing.

Ignition Delay for Neat Fuel Droplets

(range of data from the literature is included)



* Saitoh et., al, *Combustion and Flame* (1982)

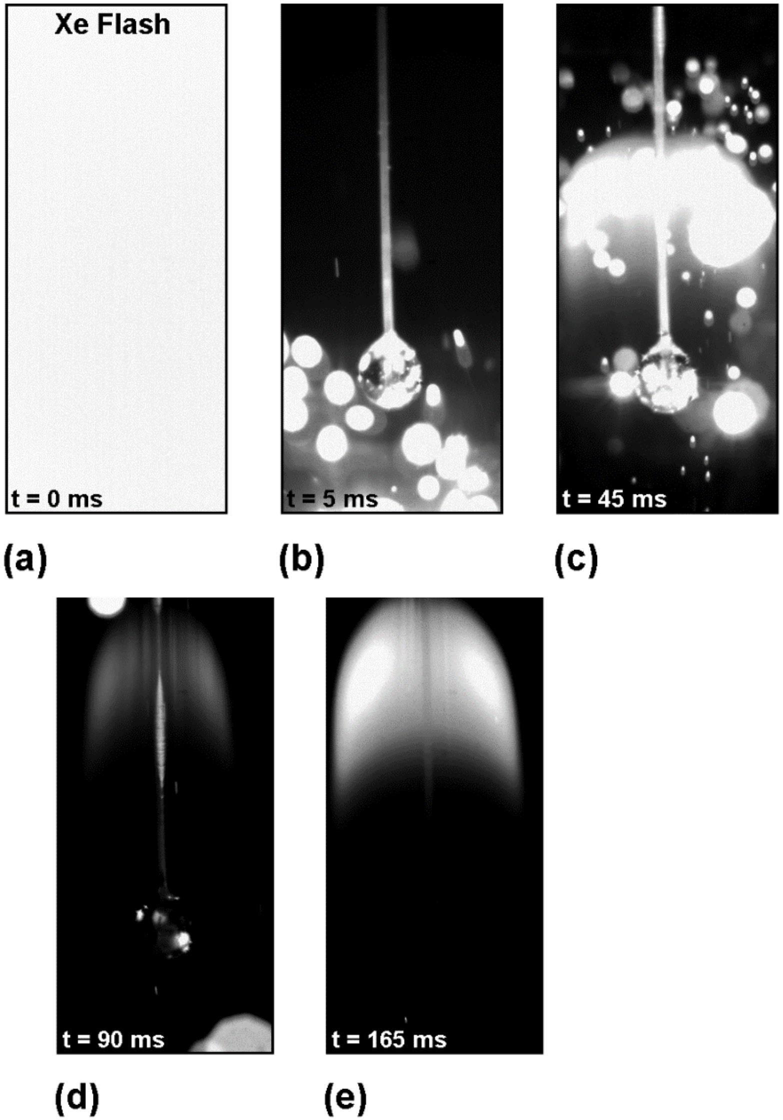
\+ Tanabe et., al, *Proc. Combust. Inst.* (1996)

‡ Dahyabhai & Rathod, *IJAERD.* (2014)

± Javed et., al, *Intrn. Heat Transfer Symp.* (2014)

- Photoignition and plasma arc ignition provide a short duration ignition transient that typically lasts <120 ms for all fuels.
- Longer ignition delays are associated with slower ignition methods such as a heated wire or introducing droplet to hot surroundings/box.

High-Speed Images of Droplet Ignition: Heptane as an Example



Different Ways of Introducing Nanoparticles (NPs) as Fuel Additives

- Typical NP additives include metals, metallic alloys, their compounds/oxides and carbon nanostructures:

  - These additives may form a solid dispersant in hydrocarbon fuels, often requiring addition of an organic surfactant

  - Most of the work reported in the literature is focused on the above

  - Achieving nano-dispersion of NPs in most fuels is quite challenging

- Some energetic compounds such as ammonia-borane may partially dissolve in a fuel:

  - We have studied the above, but there are very few reports on such additives

- It is possible to dissolved an additive in a solvent and form a fine liquid emulsion with a hydrocarbon (HF) fuel:

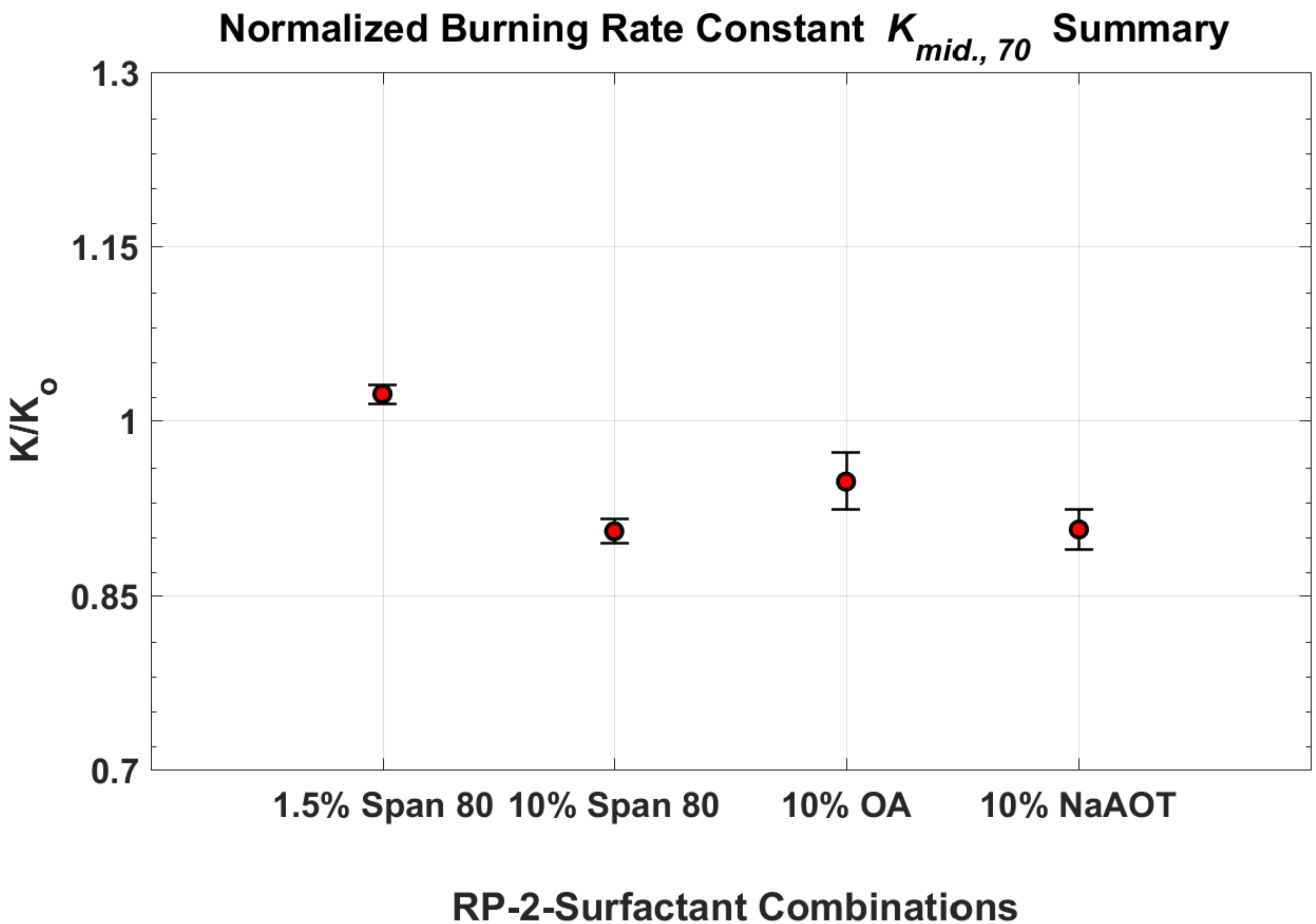
  - We did not study the above and no reports on the this is found in the literature

Study of *K* for HC Nanofuels
(mostly RP-2 & Ethanol + NP additives)

Guided by some recent reports, where they show sizable change in *K*, we performed series of 5-15 identical tests on suspended nanofuel (NF) droplets utilizing following NP additives:

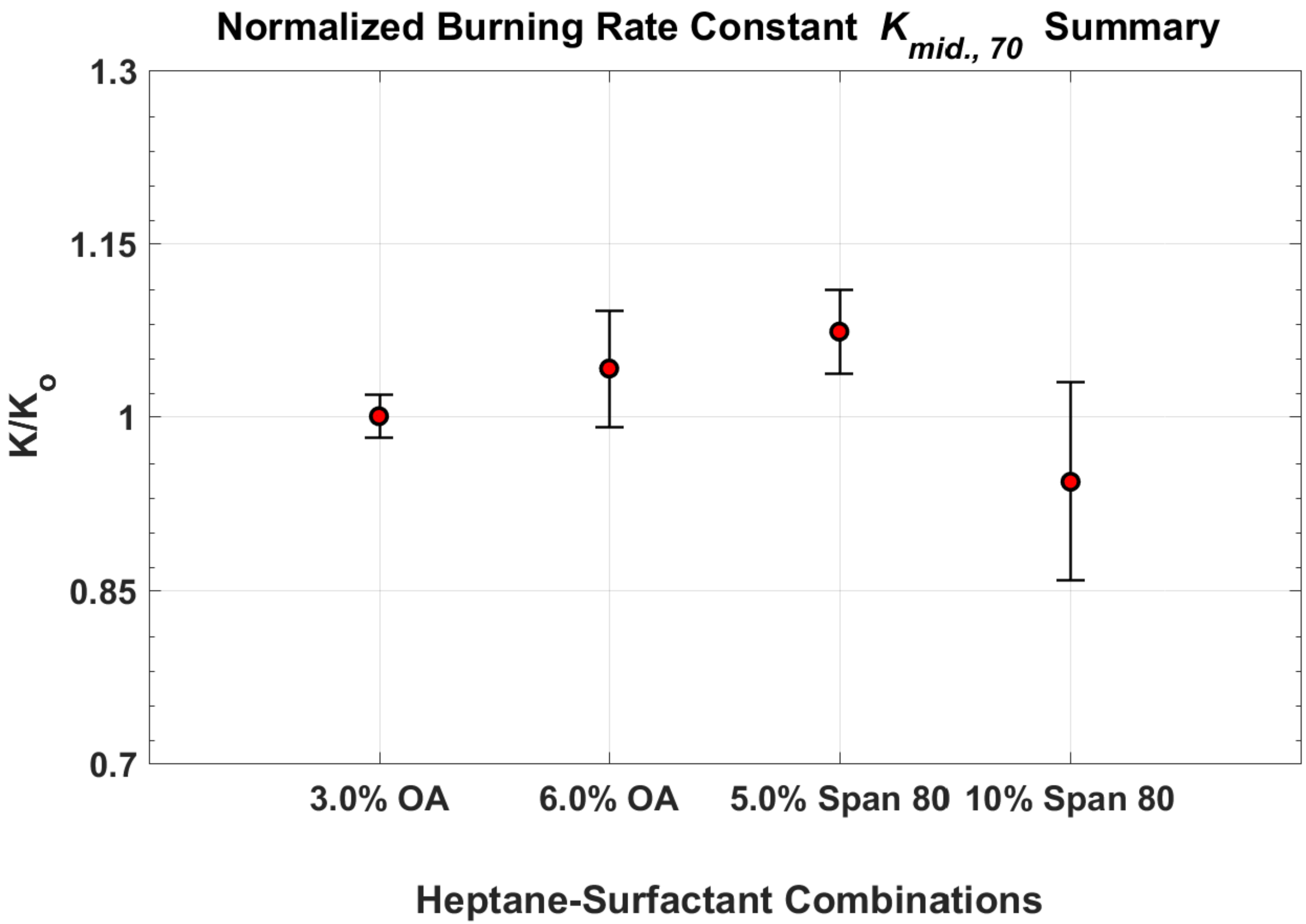
- <u>MgO</u>: Based on the work of Bello et. al., (2015) <u>RP-2 with MgO</u>
- <u>Graphene nano-platelet (GNP) additives</u>: Based on the work of Ghamari et. al., (2017), Jet-A with graphene nano-platelets (GNP)
- <u>B/Na-based soluble additives</u>: Based on the work at Purdue, Pfeil et., al., (2013), Ethanol with Ammonia Borane
- <u>nAl (80 nm)</u>: Based on the work performed at UCLA and others, different hydrocarbon fuels with nAl
- <u>Graphene</u>: Based on a sample from previous SBIR study for AFRL, RP-2 with graphene flacks additive

Surfactant Addition Sensitivity: RP-2
(for most frequently used organic compounds)



$K_{mid.,70}$ for RP-2 fuel with Span 80, Oleic Acid (OA) or Sodium Bis(2-Ethylhexyl) Sulffosuccinate (NaAOT) surfactant

Surfactant Addition Sensitivity: Heptane



$K_{mid.,70}$ for Heptane (C_7H_{16}) fuel with Oleic Acid (OA) or Span 80 surfactant (larger error bars are due to fewer tests in each case)

Reported Work on RP-2/MgO*

- They used 20 nm MgO dispersed in RP-2 using 1:10 wt ratio of Oleic Acid
- Ignition method was stationary Ni-Cr heating coil
- Initial droplet size: ~2 mm
- Fiber diameter: 1 mm
- Reported 270 fold increase for 0.5% MgO in RP-2*

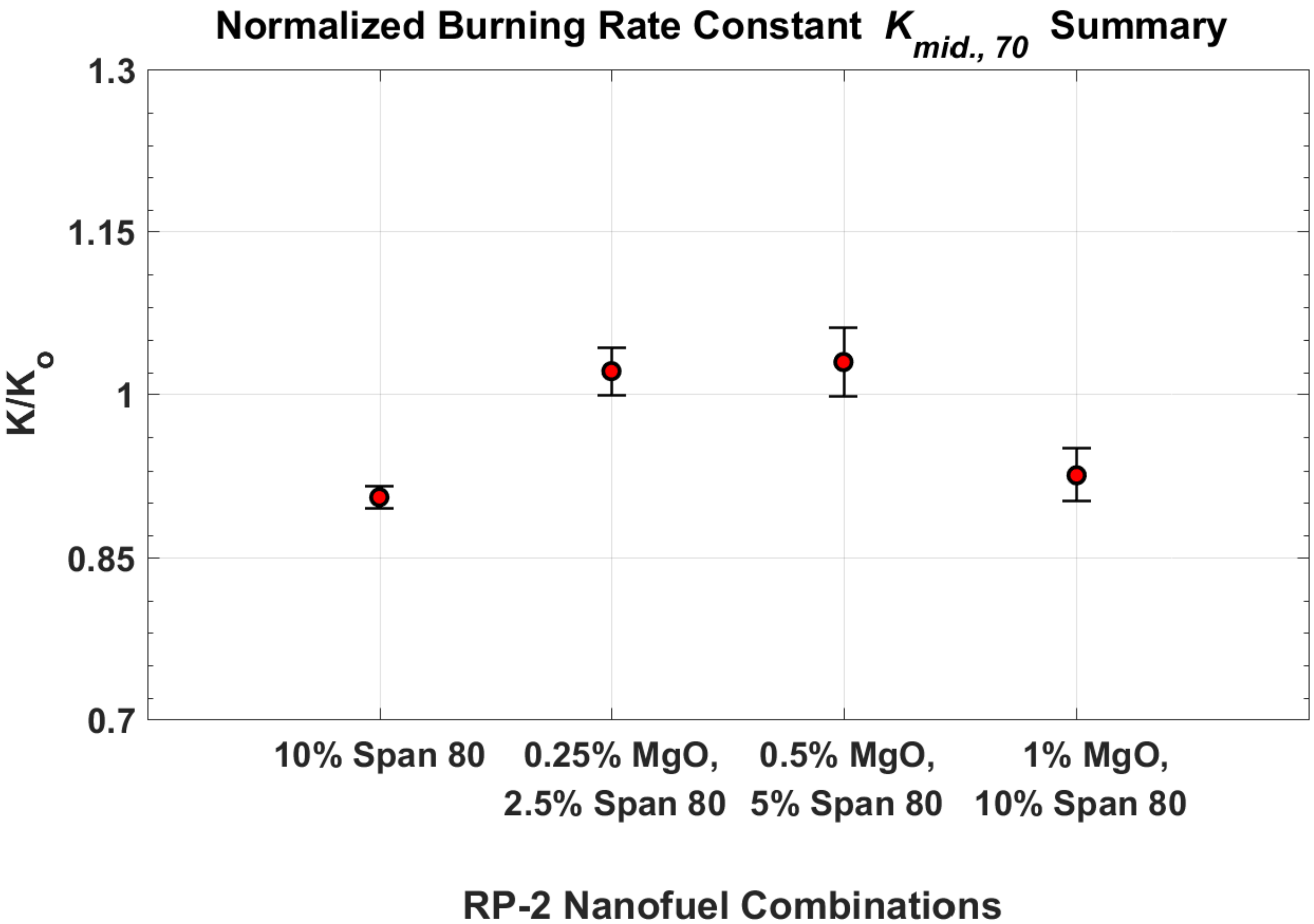
Table 3. Time Durations (in Milliseconds) and Burn Rate Constants for Stages of Regression with Varying MgO Concentrations

MgO (wt %)	stage 1 duration (ms)	stage 2 duration (ms)	K_b stage 2 (mm^2/s)	stage 3 duration (ms)	K_b stage 3 (mm^2/s)
0	300	830	0.414	N/A	N/A
0.05	92	98	8.554	170	0.46
0.25	19	11	69.97	19	2.85
0.50	3	3	111.8	4	47.59
0.75	9	8	16.95	12	53.67
1	122	328	3.075	719	2.71

Quasi-steady Burn Phase

* All data from: Bello et. al, *Energy & Fuels* 29 (9), pp. 6111–6117, (2015)

Evaluation of K for RP-2/MgO



$K_{mid.,70}$ for RP-2 fuel with Span 80 surfactant (10:1 wt Ratio) with varying MgO concentrations

Reported Work on Jet-A and Graphene Nano-platelets (GNP)*

- Used GNP dispersed in Jet-A kerosene, using 1.5% wt Span 80
- GNP Specification: 6-8 nm

thick platelets with D~5 μm

- Ni-Cr heating coil ignitor
- Initial droplet size: ~2 mm
- Fiber size: 3X16 μm SiC fibers
- Reported ~7% max increase at 0.1% wt. GNP that was attributed to absorption of heat by the darkened fuel

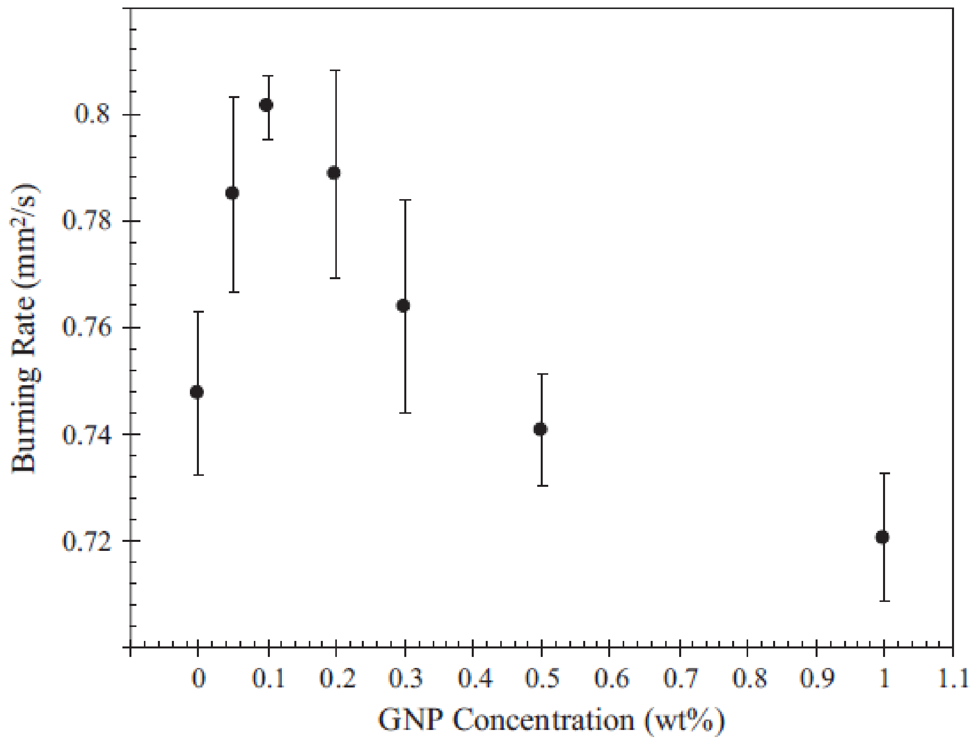
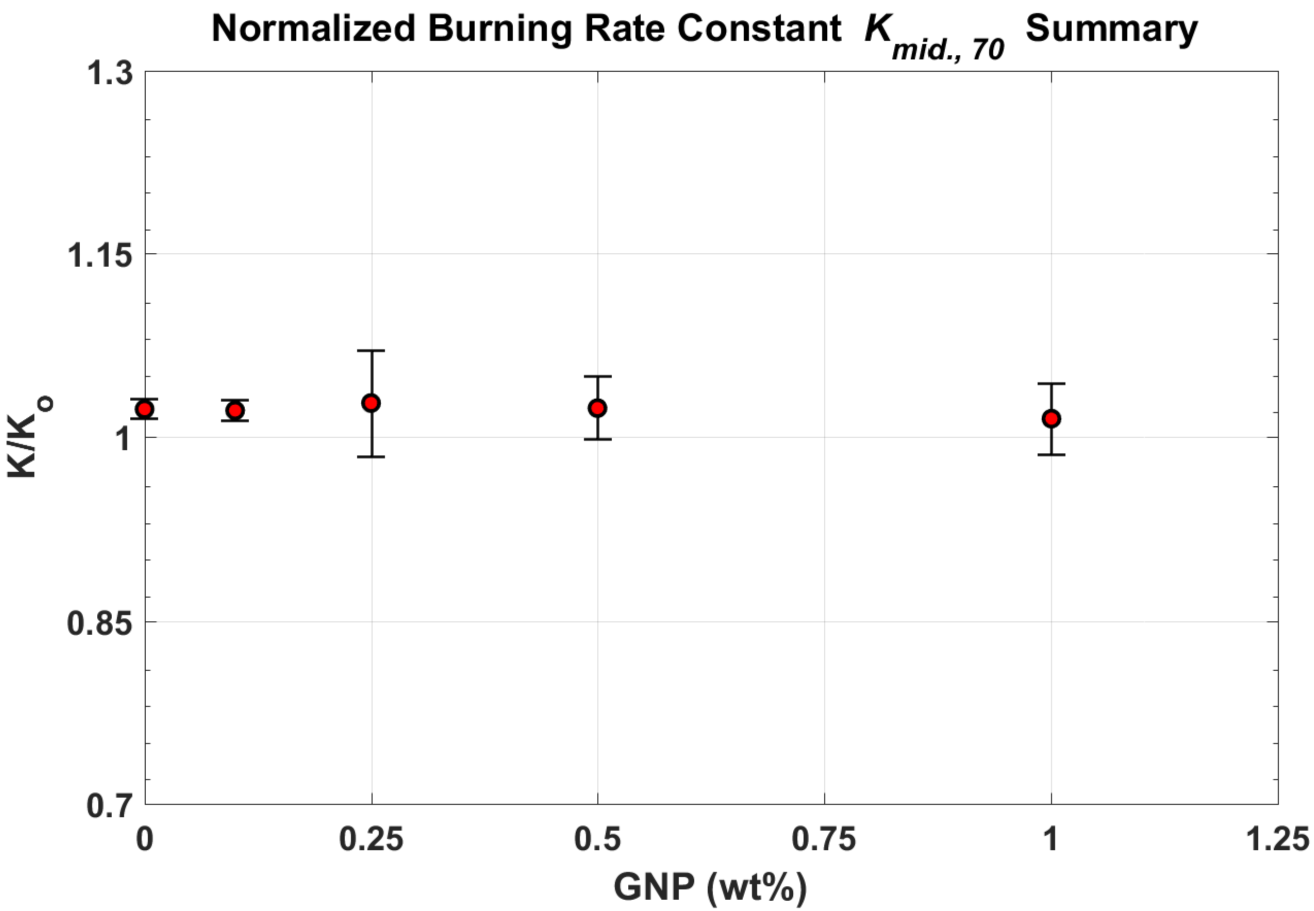


Fig. 9. Burning rate as a function of GNP concentration within jet fuel droplets. Each data point represents an average of at least five repetitions and the error bars show the corresponding standard deviation.

* All data from: Ghameri et. al, *Fuel* 118, pp. 182–189, (2017)

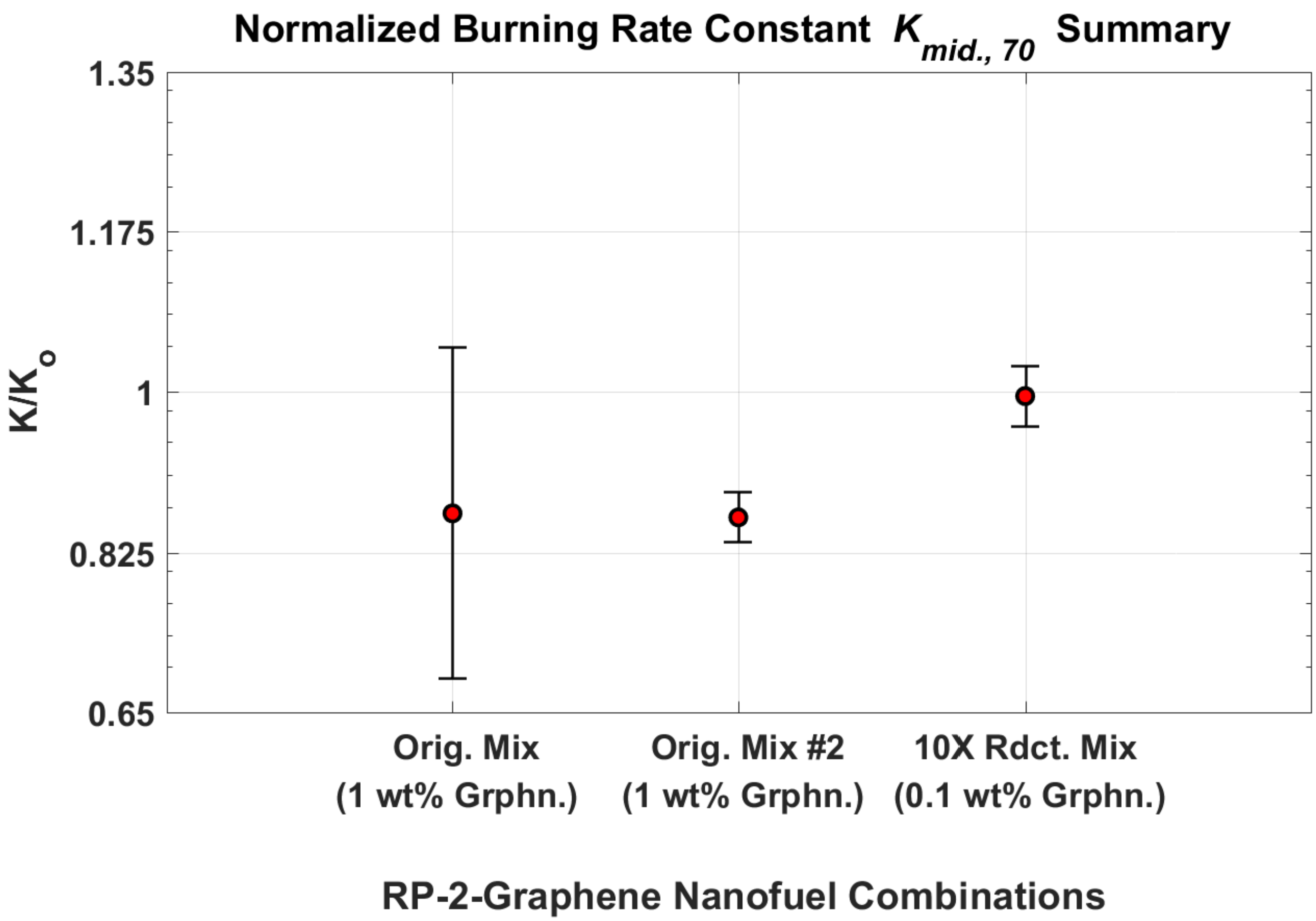
Evaluation of *K for* RP-2/GNP



$K_{mid.,70}$ for RP-2 and Span 80 (1.5% wt.) with low concentrations of GNPs

Our fast-acting ignition and the exclusion of the first 15% of the burning curve minimizes any possible effects of the ignition method

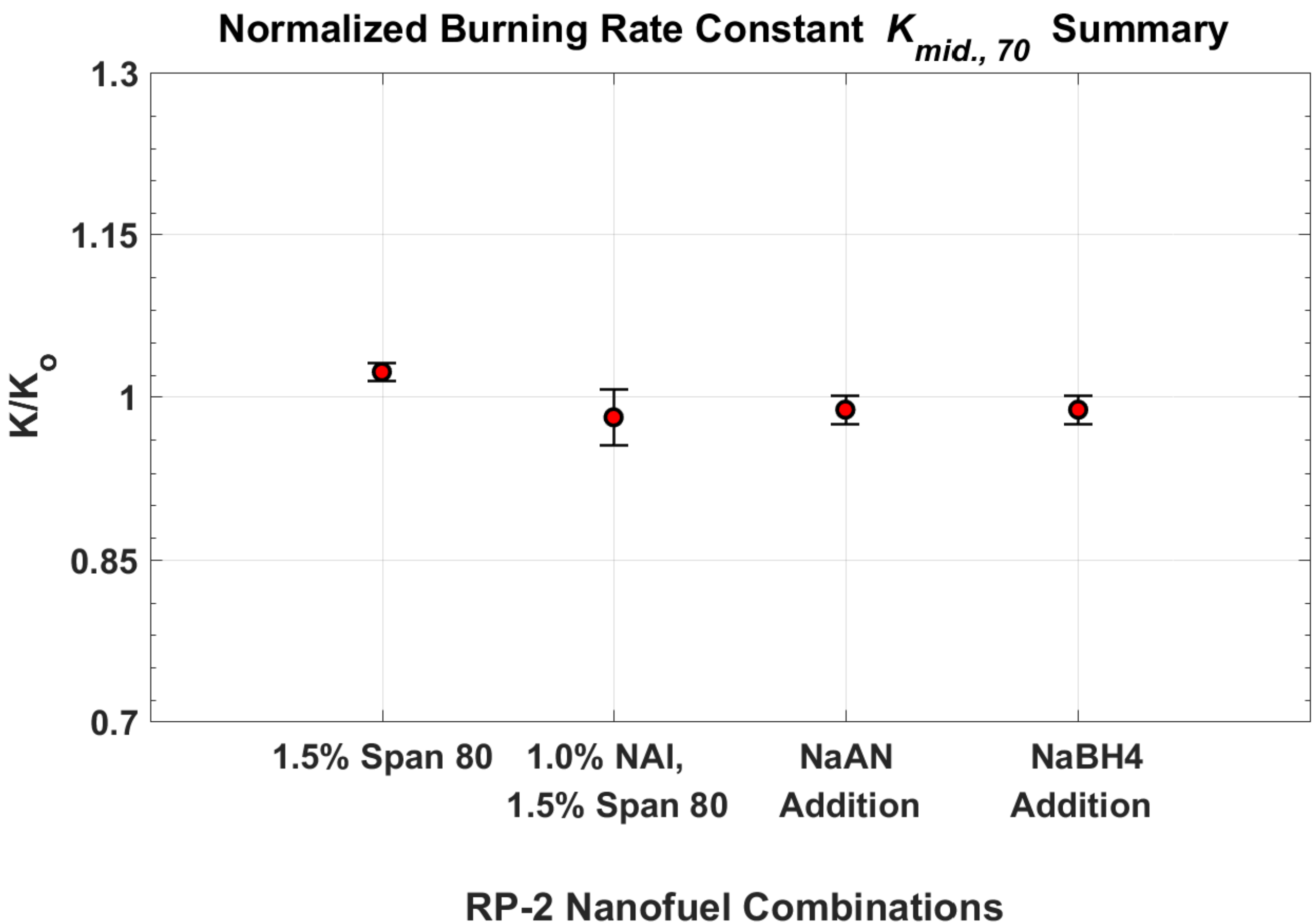
Evaluation of *K* for RP-2/Graphene



$K_{mid.,70}$ for RP-2 and a surfactant with two different concentration of graphene

The larger error bar is due to an uncertainty in the concentration of the original mix

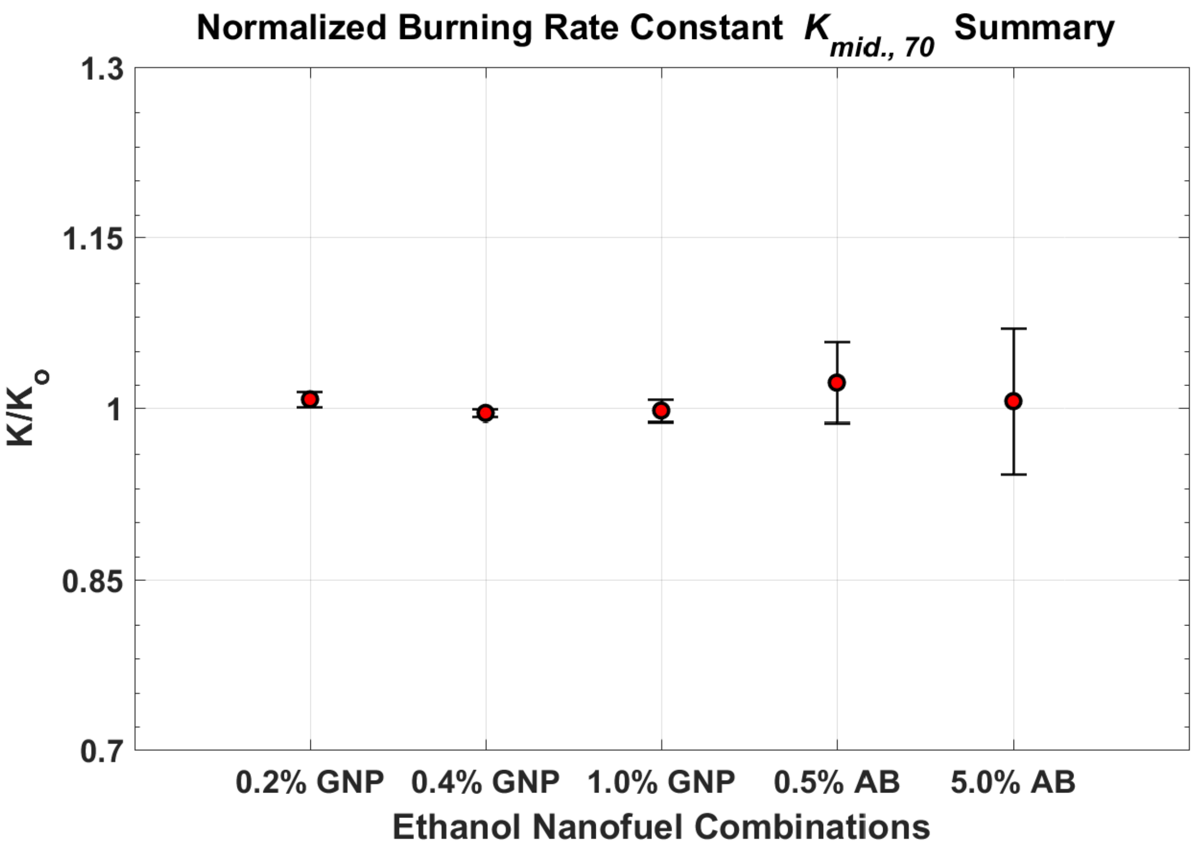
Evaluation of *K* for RP-2 with Nano-Al (nAl) and Soluble Energetic Compounds



$K_{mid.,70}$ for RP-2 and Span 80 (1.5% wt.) with 80 nm nAl

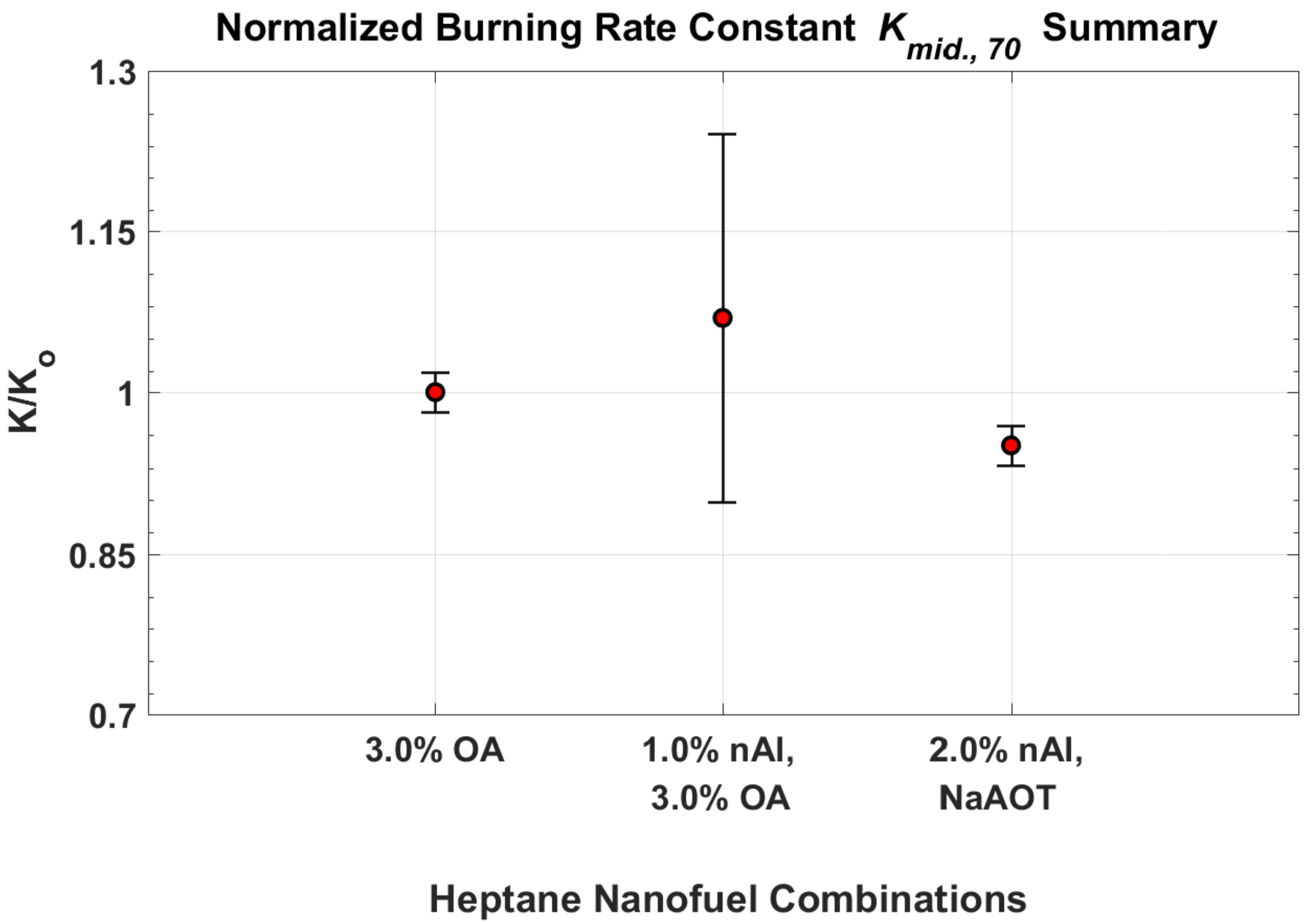
The unknown concentration of NaAN and NaBH4 was the Max. that was soluble in RP-2

Evaluation of *K* for Various Ethanol Nanofuels



- $K_{mid.,70}$ for ethanol with varying GNP and Ammonia Borane concentrations (no surfactant)
- Pfeil, et. al., *Combustion and Flame* (2013), reported 16% increase in *K* for 6% AB (the Max. solubility of AB in Ethanol)

Evaluation of *K* for Heptane with nAl



$K_{mid.,70}$ for heptane fuel with oleic acid (OA) or NaAOT as a surfactant

oleic acid produced relatively poor suspension of nAl in heptane

Conclusions

Burning Characteristics of Suspended Droplets of Neat Fuels:

- New fast-acting ignition methods provide well defined measures of burning rate constants, *K,* and ignition delays in hydrocarbon fuel droplets.

-Burning rate constants, *K,* measured well after ignition transient and they are unaffected by the ignition method.

-K for neat fuels are in general agreement with the values reported by others

-Measured ignition delays are much shorter than reported values in the literature obtained by more conventional methods (where substantial heating is involved.)

Burning Characteristics of Suspended Droplets of Nanofuels:

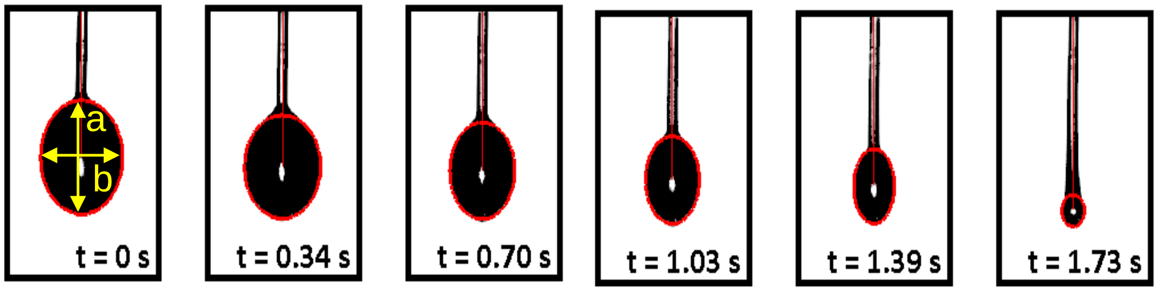
- Effect of addition of modest amount of surfactants on *K* is minimal
- For moderately loaded nanofuels (<5%) the change in burning rate constant is relatively small (<10%).

- Effects of most additives are only noticed later in droplet lifetime when the NPs become concentrated
- We observed little change in *K* for dissolved NFs, but have seen qualitative effects such as change in flame color and foaming of the fuel at the end.

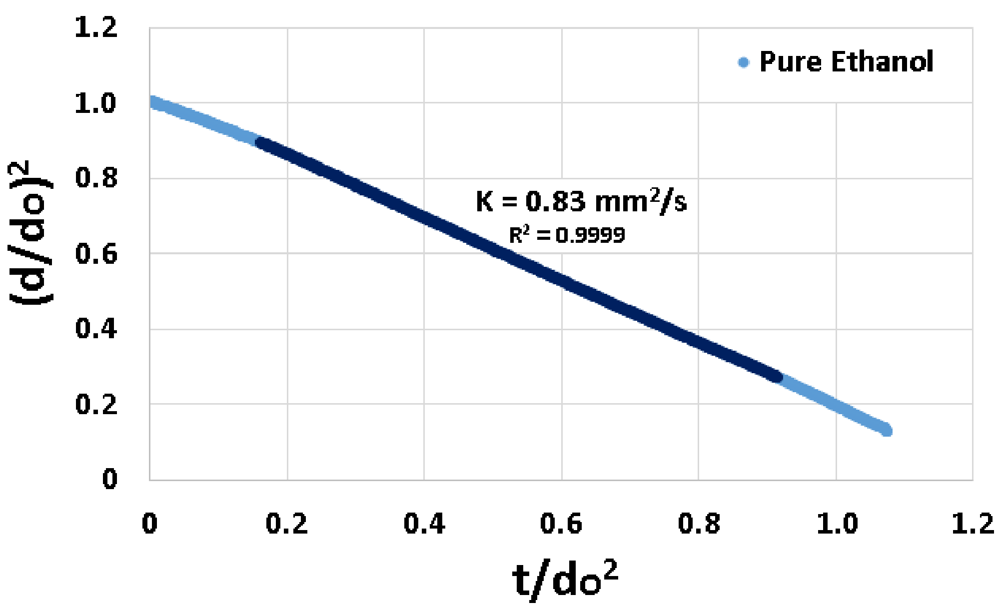
Backup Slides

Droplet Regression and Evaluation of *K* (Ethanol Example)

Droplet Burning Time Sequence



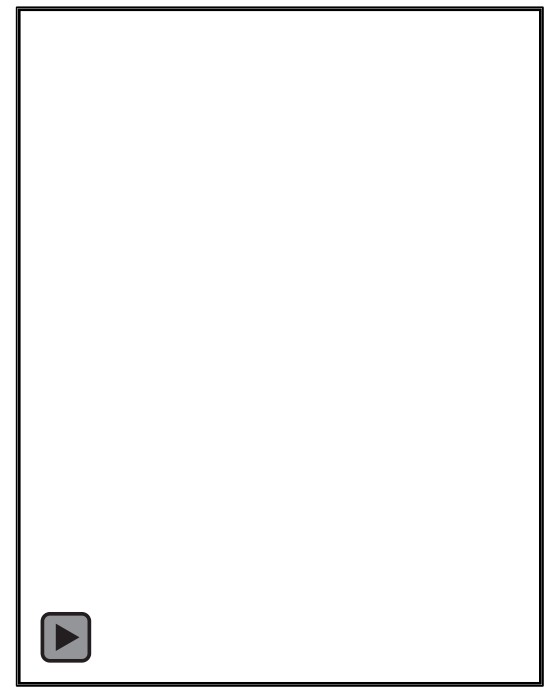
Normalized Droplet Regression



Burning Rate *K* Calculation

$$K = \frac{d}{dt}\left(d_{\text{eqvs}}\right)^2, \text{ where}$$

$$d_{\text{eqvs}} = 2a^{2/3}b^{1/3}$$



Ethanol Droplet Burning.

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited PA 17513

Ignition Delay in Fuel Droplets

- Ignition delay $(\tau_{ign.})$ is typically defined as the time a droplet is introduced to a hot environment until the droplet flame becomes fully established*.

  - Traditionally thought of a property of the fuel.
  - $\tau_{ign.}$ decreases as $T_{l.S.}$ increases (data available up to 1300 K.)
  - $\tau_{ign.}$ decreases as P_c increases (planned for future works.)

- All of the above trends were observed via introducing the droplet to a hot environment/filament relatively slowly, >0.5 s.
- Under such conditions, a direct/visual indication of the onset of combustion is impractical due to luminous background.
- However, reasonable estimates of $\tau_{ign.}$ for fuel droplets can be achieved using photoignition and plasma arc ignition.

* Aggarwal, *Progress in Energy and Combustion Science* (2014)